VECTOR BOSON SCATTERING AT THE LHC

A study of the $WW \to WW$ channels with the Warsaw cut

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[with M. Fabbrichesi, M. Pinamonti and A. Urbano, arXiv:1509.06378]

Program on Particle Physics at the Dawn of the LHC13

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International Centre for Theoretical Physics
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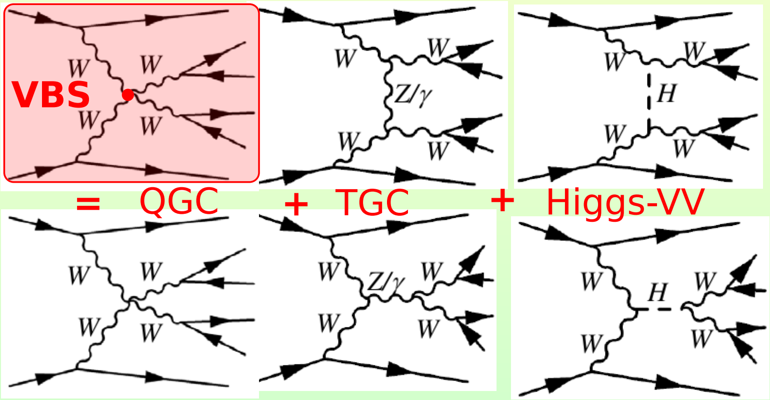
unesp IFT

WW scattering

WW scattering diagrams at LHC

WW scattering in proton-proton collisions



Motivations

- Vector boson scattering (VBS) at the LHC provides a direct window on the mechanism responsible for electroweak (EW) symmetry breaking
- Modifications of SM gauge trilinear, quartic and Higgs boson couplings lead to terms proportional to E_{WW}^4 and E_{WW}^2 in longitudinal gauge boson scattering amplitude
- All these potential departures from the SM represent signals for new physics and can be described in a model independent way by means of an effective field theory
- Experimental measurement of $pp \to WWjj$ can constrain the coefficients of the effective lagrangian and pin down the physics behind the EW symmetry breaking

The story so far

- 1985: First theoretical study of signatures of strongly interacting W/Z bosons in $pp \to VV + X$ at hadron supercolliders $\sqrt{s} = 10$-40 TeV using effective W approximation. [*M. Chanowitz and M. Gaillard, NPB 261 379; M. Duncan, G. Kane and W. Repko, NPB 272 517.*]
- 1988: Study of same-sign longitudinal WW production at SSC as probe of EWSB sector. [*M. Chanowitz and M. Golden, PRL 61 1053; 63 466.*]
- 1990-1995: Study of $pp \to VVjj$ at hadron supercolliders in the purely leptonic channels (Gold-Plated Modes). Develop optimized cuts (tag jets, jet veto and back-to-back leptons) for signal identification at SSC and LHC. [*V. Barger, K. Cheung, T. Han and R. Phillips, PRD 42 3052; J. Bagger, V. Barger, K. Cheung, J. Gunion, T. Han, G. Ladinsky, R. Rosenfeld and C. Yuan, PRD 49 1246; 52 3878.*]

The story so far

- 1998: Study of anomalous quartic boson interactions through $pp \to VVjj$ production at LHC. Full tree level calculation of the processes using `HELAS` and `MADGRAPH`. Derivation of expected bounds on EW chiral lagrangian coefficients. [A. Belyaev, O. Eboli, M. Gonzalez-Garcia, J. Mizukoshi, S. Novaes and I. Zacharov, PRD 59 015022.]
- 2002: Study of elastic WW sattering at LHC in the semileptonic channel with `PYTHIA` using the EW chiral lagrangian applying different unitarization protocols. [J. M. Butterworth, B. E. Cox and J. R. Forshaw, PRD 65 096014.]
- 2006: Study of anomalous quartic boson interactions through $pp \to ll\nu\nu + 2j$ production at LHC. Full tree-level six-particle final state calculation of the processes at $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha^4\alpha_S^2)$ using `HELAS` and `MADGRAPH`. [O. Eboli, M. Gonzalez-Garcia and J. K. Mizukoshi, PRD 74 073005.]

The story so far

- 2006-2011: Complete parton-level study of $pp \to l\nu + 4j$, $pp \to lll\nu + 2j$, $pp \to 4l + 2j$ and $pp \to ll\nu\nu + 2j$ at $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha^4\alpha_S^2)$ and $\mathcal{O}(\alpha^2\alpha_S^4)$ using exact matrix element computations with `PHASE` and `PHANTOM`. Develop kinematics cuts to enhance VV scattering component over background in SM Higgs and SILH scenarios. [E. Accomando, A. Ballestrero, S. Bolognesi, E. Maina and C. Mariotti, JHEP 0603, 093 (2006) [hep-ph/0512219]; A. Ballestrero, G. Bevilacqua and E. Maina, JHEP 0905, 015 (2009) [arXiv:0812.5084 [hep-ph]]; A. Ballestrero, G. Bevilac- qua, D. B. Franzosi and E. Maina, JHEP 0911, 126 (2009) [arXiv:0909.3838 [hep-ph]]; A. Ballestrero, D. B. Franzosi, E. Maina, JHEP 1106 (2011) 013.]

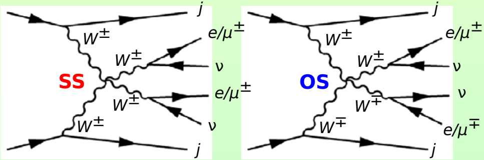
The story so far

- 2012: Propose a new variable (R_{p_T}) to improve the isolation of $W_L W_L$ component in the same-sign $pp \to WWjj$ production at the LHC in the purely leptonic channels. [K. Doroba, J. Kalinowski, J. Kuczmarski, S. Pokorski, J. Rosiek, M. Szleper and S. Tkaczyk, PRD 83 036011.]

Other references: A. Dobado, M. J. Herrero and J. Terron, Z. Phys. C 50, 205 (1991); A. Dobado, M. J. Herrero, J. R. Pelaez, E. Ruiz Morales and M. T. Urdiales, Phys. Lett. B 352, 400 (1995); A. Alboteanu, W. Kilian and J. Reuter, JHEP 0811, 010 (2008); T. Han, D. Krohn, L. T. Wang and W. Zhu, JHEP 1003, 082 (2010); C. Englert, B. Jager, M. Worek and D. Zeppenfeld, Phys. Rev. D 80, 035027 (2009); A. Freitas and J. S. Gainer, Phys. Rev. D 88, no. 1, 017302 (2013); W. Kilian, T. Ohl, J. Reuter and M. Sekulla, Phys. Rev. D 91, 096007 (2015); D. Espriu and B. Yencho, Phys. Rev. D 87, no. 5, 055017 (2013); D. Espriu and F. Mescia, Phys. Rev. D 90, no. 1, 015035 (2014); R. L. Delgado, A. Dobado and F. J. Llanes-Estrada, J. Phys. G 41, 025002 (2014).

Our study

- Consider a scenario where possible new physics resonances do NOT lie within the LHC reach
- Parametrize new physics effects in the Higgs sector by means of an effective lagrangian
- Derive expected exclusion limits and discovery significance of effective operator coefficients by looking at $pp \to WWjj \to l\nu l\nu jj$ at LHC, using the R_{p_T} cut
- Different luminosity benchmarks are considered for LHC Run 2, Run 3 and beyond



Effective lagrangian

Non-linear lagrangian

Leading order lagrangian (SM: $a = b = 1$)

$$\mathcal{L}_0 = \frac{v^2}{4}\left[1 + 2\,a\,\frac{h}{v} + b\left(\frac{h}{v}\right)^2\right]\mathrm{Tr}\left[(D_\mu U)^\dagger (D^\mu U)\right] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) - \frac{1}{2}\mathrm{Tr}\,\hat{W}_{\mu\nu}\hat{W}^{\mu\nu} - \frac{1}{2}\mathrm{Tr}\,\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}$$

(Would-be) Goldstone boson matrix ($v = 246$ GeV $\alpha = 1, 2, 3$)

$$U = \exp(i\pi^\alpha \sigma_\alpha / v)$$

Covariant derivative ($\hat{W}_\mu \equiv \sigma_\alpha W_\mu^\alpha / 2$, $\hat{B}_\mu \equiv \sigma_3 B_\mu / 2$)

$$D_\mu U = \partial_\mu U + ig\hat{W}_\mu U - ig' U \hat{B}_\mu$$

Higher dimensional operators

Add the following set of higher dimensional operators (custodial invariant in the limit $g' \to 0$)

$$
\begin{aligned}
\mathcal{L}_1 \quad = \quad & \frac{1}{2} a_1 g g' B_{\mu\nu} \mathrm{Tr}\,(T \hat{W}^{\mu\nu}) \\
& + \frac{i}{2} a_2 g' B_{\mu\nu} \mathrm{Tr}\,(T [V^\mu, V^\nu]) \\
& + 2 i a_3 g \mathrm{Tr}\,(\hat{W}_{\mu\nu} [V^\mu, V^\nu]) \\
& + a_4 \left[\mathrm{Tr}\,(V_\mu V_\nu)\right]^2 \\
& + a_5 \left[\mathrm{Tr}\,(V_\mu V^\mu)\right]^2
\end{aligned}
$$

Blocks

$$V_\mu = (D_\mu U) U^\dagger \qquad T \equiv U \sigma_3 U^\dagger$$

Transformation properties ($L \in SU(2)_L$, $R \in U(1)_R$)

$$U \to L U R^\dagger$$

Contributions to aTGC

Anomalous triple gauge couplings lagrangian

$$\begin{aligned}\mathcal{L}_{\rm TGC} \;&=\; ie\Big[g_1^\gamma A_\mu\left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu}\right) + \kappa^\gamma W_\mu^- W_\nu^+ A^{\mu\nu} \\ &+\frac{\lambda^\gamma}{m_W^2} W_\mu^{-\nu} W_{\nu\rho}^+ A^{\rho\mu}\Big] + \frac{iec_W}{s_W}\Big[g_1^Z Z_\mu\big(W_\nu^- W^{+\mu\nu} \\ &-W_\nu^+ W^{-\mu\nu}\big) + \kappa^Z W_\mu^- W_\nu^+ Z^{\mu\nu} + \frac{\lambda^Z}{m_W^2} W_\mu^{-\nu} W_{\nu\rho}^+ Z^{\rho\mu}\Big]\end{aligned}$$

SM values: $g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1$, $\lambda^{\gamma,Z} = 0$. Modifications due to the effective operators

$$\Delta g_1^Z = \frac{g'^2}{c_W^2 - s_W^2} a_1 + \frac{2g^2}{c_W^2} a_3 \qquad \Delta\kappa^\gamma = g^2(a_2 - a_1) + 2g^2 a_3$$

$$\Delta\kappa^Z = \frac{g'^2}{c_W^2 - s_W^2} a_1 - g'^2(a_2 - a_1) + 2g^2 a_3$$

Contributions to aQGC

$$
\begin{aligned}
\mathcal{L}_{QGC} &= e^2 g_{WWVV}\left[g_1^{VV} V^\mu V^\nu W_\mu^- W_\nu^+ - g_2^{VV} V^\mu V_\mu W^{-\nu} W_\nu^+\right] \\
&+ \frac{e^2 c_W}{s_W}\Big[g_1^{\gamma Z} A^\mu Z^\nu (W_\mu^- W_\nu^+ + W_\mu^+ W_\nu^-) \\
&\quad -2 g_2^{\gamma Z} A^\mu Z_\mu W^{-\nu} W_\nu^+\Big] + \frac{e^2}{2 s_W^2}\Big[g_1^{WW} W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ \\
&\quad - g_2^{WW} (W^{-\mu} W_\mu^+)^2\Big] + \frac{e^2}{4 s_W^2 c_W^4} h^{ZZ} (Z_\mu Z^\mu)^2
\end{aligned}
$$

SM values: $g_{1/2}^{VV'} = 1$, $h^{ZZ} = 0$. Effective operators contribution

$$
\begin{aligned}
\Delta g_1^{\gamma Z} &= \Delta g_2^{\gamma Z} = \frac{2g^2}{c_W^2} a_3 \qquad \Delta g_2^{ZZ} = 2\Delta g_1^{\gamma Z} - \frac{g^2}{c_W^4} a_5 \\
\Delta g_1^{ZZ} &= 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_W^4} a_4 \qquad \Delta g_1^{WW} = 2 c_W^2 \Delta g_1^{\gamma Z} + g^2 a_4 \\
h^{ZZ} &= g^2 (a_4 + a_5) \qquad \Delta g_2^{WW} = 2 c_W^2 \Delta g_1^{\gamma Z} - g^2 (a_4 + 2 a_5)
\end{aligned}
$$

Experimental bounds

Fit of LHC Higgs data [Ellis,You, JHEP 1306, 103 (2013)]

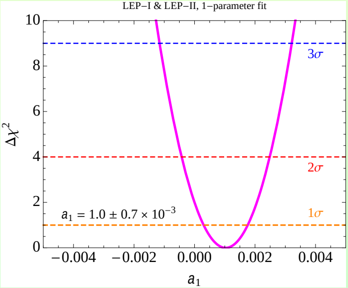
$$a = 1.03 \pm 0.06$$

The coefficient a_1 contributes at tree-level to the S parameter

$$\Delta S = -16\pi a_1$$

Fit of LEP data gives [A. Falkowski, F. Riva and A. Urbano, JHEP 1311, 111 (2013)]

$$a_1 = (1.0 \pm 0.7) \times 10^{-3}$$



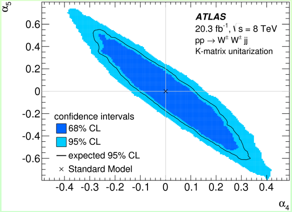
Experimental bounds

Combining the best limits coming from bounds on TGC at LEP [Phys. Lett. B 614, 7] and LHC [arXiv:1507.03268]

$$-0.24 < a_2 < 0.20 \quad \text{and} \quad -0.04 < a_3 < 0.02$$

ATLAS and CMS 95% CL bounds obtained by studying EW $W^\pm W^\pm$ production at Run 1 [Phys. Rev. Lett. 113, no. 14, 141803 (2014), CMS-PAS-SMP-13-01]

$$-0.14 < a_4 < 0.16 \quad \text{and} \quad -0.23 < a_5 < 0.24$$



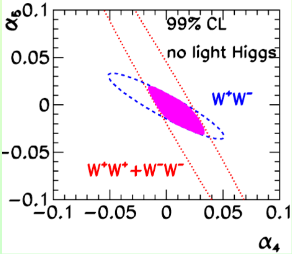
Expected bounds

ATLAS estimated bound on a_4 at the LHC Run 2 (95% CL, 300 fb^{-1}, 14 TeV) [ATLAS-PHYS-PUB-2012-005]

$$a_4 \leq 0.066$$

Best estimated limits obtained combining same- and opposite-sign WW production channels (99% CL, 100 fb^{-1}, 14 TeV) [O. Eboli, M. C. Gonzalez-Garcia and J. K. Mizukoshi, Phys. Rev. D 74, 073005 (2006)]

$$-0.01 < a_4 < 0.01 \quad \text{and} \quad -0.01 < a_5 < 0.01$$



Theoretical bounds

The causal and analytic structure of Goldstone boson amplitudes leads to

$$a_4 > 0 \quad \text{and} \quad a_4 + a_5 > 0$$

[T. N. Pham and T. N. Truong, Phys. Rev. D 31, 3027 (1985); A. Adams, N. Arkani-Hamed, S. Dubovsky, A. Nicolis and R. Rattazzi, JHEP 0610, 014 (2006) [hep-th/0602178]; J. Distler, B. Grinstein, R. A. Porto and I. Z. Rothstein, Phys. Rev. Lett. 98, 041601 (2007) [hep-ph/0604255]; L. Vecchi, JHEP 0711, 054 (2007) [arXiv:0704.1900 [hep-ph]].]

MC

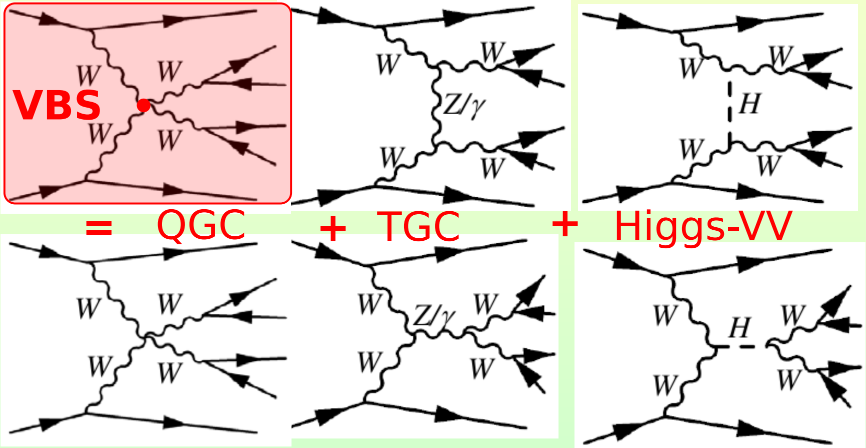
Monte Carlo simulation

- Implement the effective lagrangian in `FeynRules` and create the UFO for the model to be used in `MADGRAPH5`
- Use `MADGRAPH5` to generate $pp \to W^\pm W^\pm jj$ (SS) and $pp \to W^+W^-jj$ (OS) events at $\mathcal{O}(\alpha^4)$, $\mathcal{O}(\alpha^2\alpha_S^2)$ in presence of effective operators at tree-level
- Make the W's to decay leptonically (with `MadSpin`)
- Simulate the relevant backgrounds for each process
- Events have been showered using `Pythia6.4` and then processed through `Delphes` (for detector simulation)

$$pp \to W^{\pm}W^{\pm}jj$$

$pp \to W^{\pm}W^{\pm}jj$ Signal

EW diagrams $\mathcal{O}(\alpha^2)$: WW-scattering

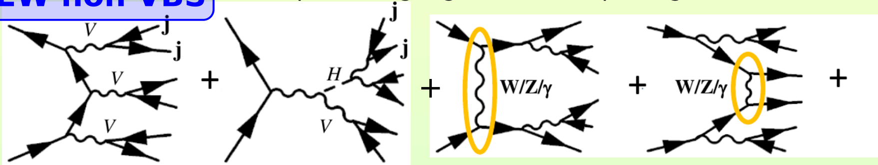


$pp \to W^\pm W^\pm jj$ Irred. Background

EW $\mathcal{O}(\alpha^2)$ and QCD $\mathcal{O}(\alpha\alpha_S)$ diagrams: the W's do not interact

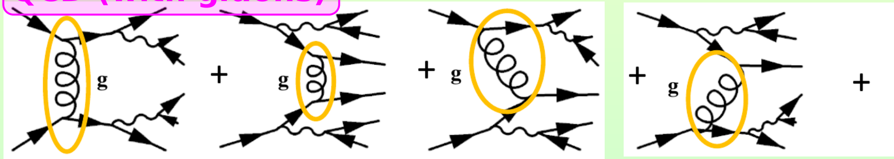
EW non-VBS

no possible gauge-invariant splitting from VBS



QCD (with gluons)

split from VBS



$pp \to W^\pm W^\pm jj$ Red. Background

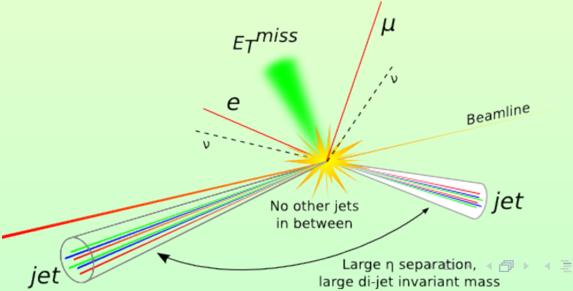
- Z+jets: this process can easily enter if the sign of one lepton is misidentified
- $t\bar{t}$: same as for Z+jets but in principle harder to suppress due to more energetic jets and lepton pairs with large angular separation and higher invariant masses
- WZ+jets, $t\bar{t}W$, $t\bar{t}Z$ and $t\bar{t}H$: high energy jets together with MET and two or more charged leptons
- single-lepton+jet (*e.g.* from W+jets): these events can enter if a jet is misidentified as an additional isolated lepton

Only WZ+jets background considered because the others are highly suppressed by the cuts (BUT our Monte Carlo simulation does not predict correctly lepton and jet misidentification).

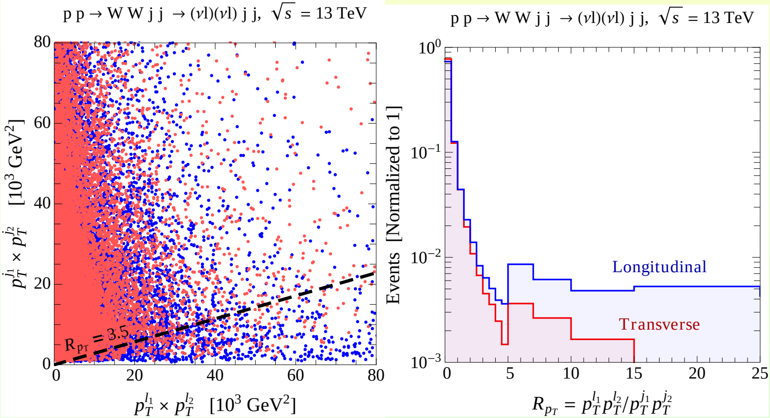
Cuts

We select events by requiring:

- two same-sign leptons (e or μ) with $p_T^{l^\pm} > 20$ GeV and $|\eta_{l^\pm}| < 2.5$
- at least two jets ($p_T^j > 25$ GeV and $|\eta_j| < 4.5$) with relative rapidity $|\Delta y_{jj}| > 2.4$
- hardest p_T jets with an invariant mass $m_{jj} > 500$ GeV
- missing transverse energy $E_T^{miss} > 25$ GeV
- $R_{p_T} = \frac{p_T^{l_1}\ p_T^{l_2}}{p_T^{j_1}\ p_T^{j_2}} > 3.5$



R_{p_T} variable cut



Improves the selection of longitudinal W's

Cut flow

Signal S:

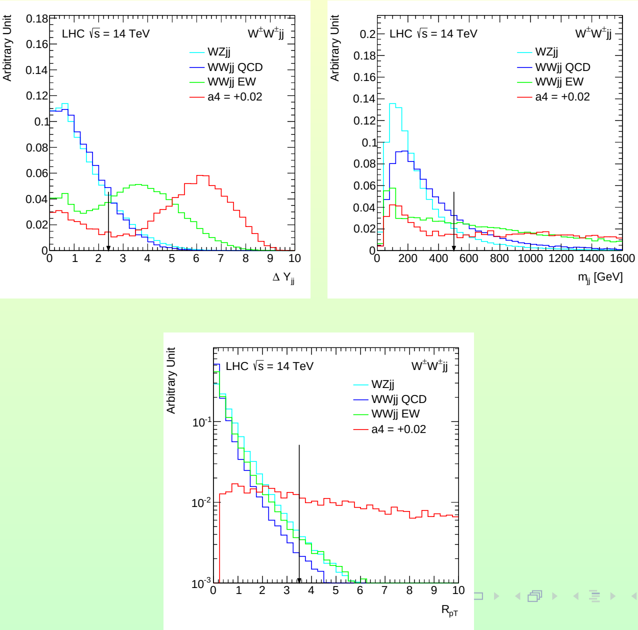
$$S = \mathcal{N}_{\text{ev}}(pp \to WWjj)\Big|_{a,a_2,a_3,a_4,a_5} - \mathcal{N}_{\text{ev}}(pp \to WWjj)\Big|_{a=1,a_i=0}$$

Background B:

$$B = \mathcal{N}_{\text{ev}}(pp \to WWjj)\Big|_{a=1,a_i=0} + \mathcal{N}_{\text{ev}}(pp \to WZjj)\Big|_{a=1,a_i=0}$$

$\sqrt{s} = 14$ TeV, 300 fb^{-1}				
CUT	$WZjj$	$WWjj$QCD	$WWjj$EW	S ($a_4 = 0.02$)
2 SS leptons	4474	778	1343	1289
$E_T^{miss} > 25$ GeV	3705	703	1225	1262
$\Delta y_{jj} > 2.4$	536	181	746	900
$m_{jj} > 500$ GeV	330	60	678	890
$R_{p_T} > 3.5$	6.5	0.5	17	747

Discriminating variables



Unitarity violation

Violation of unitarity for $a \neq 1$, $a_i \neq 0$ can be understood by looking at the longitudinal W bosons scattering amplitudes in the massless, gaugeless limit using equivalence theorem

$$A(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm) = A_2$$

Partial waves (A_I isospin waves)

$$t_{IJ}(s) = \frac{1}{64\pi} \int_{-1}^{1} d\cos\theta \, A_I(s,t) P_J(\cos\theta)$$

Leading wave $J = 0$

$$t_{20} \quad = \quad -\frac{s}{32\,\pi v^2}(1 - a^2 - 6g'^2 a_2 + 12 g^2 a_3) + \frac{s^2}{6\,\pi v^4}\left[a_5 + 2\,a_4 - g'^2 a_2^2 - 4 g^2 a_3^2\right]$$

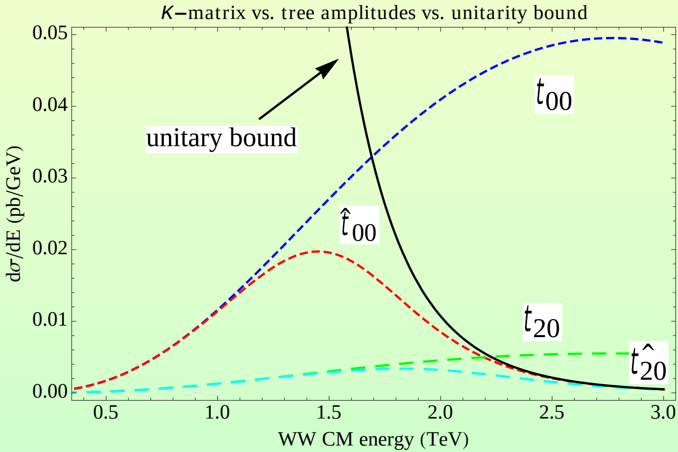
Unitarity requires

$$|t_{IJ}(s)| < 1 \qquad\qquad \operatorname{Im} t_{IJ}(s) = |t_{IJ}(s)|^2$$

Unitarization

K-matrix unitarization prescription

$$\hat{t}_{IJ}(s) = \frac{\mathrm{Re}\, t_{IJ}(s)}{1 - i\mathrm{Re}\, t_{IJ}(s)}$$



Unitarization

A treatment consistent with unitarity can be obtained by

- implementing the K-matrix prescription and re-weighting each event, depending of its energy, by

$$\frac{|\hat{t}_{20}|^2}{|t_{20}|^2}$$

- use a sharp cutoff unitarization by cutting off events with $m_{WW} > 1.25$ TeV
- introduce an ad-hoc form factor in the effective vertex

$$\left(1 + \frac{q^2}{\Lambda^2}\right)^{-n}$$

We use the first two methods (give equivalent results)

Statistical analysis

- Poisson probability of observing n events with μ expected:

$$P(n|\mu) = \frac{e^{-\mu}\mu^n}{\Gamma(n)}$$

- 95 % CL limits if

$$\int_{n<B} P(n|S+B) < 0.05$$

- '5σ' discovery significance if

$$\int_{n>S+B} P(n|B) < p_0^{5\sigma}$$

- In case of large number of events we can use $S/\sqrt{S+B}$ for limits and $S/\sqrt{B}$ for significance

Results

$\sqrt{s} = 13$ **TeV** **L=100 fb**$^{-1}$

1D limits and significance

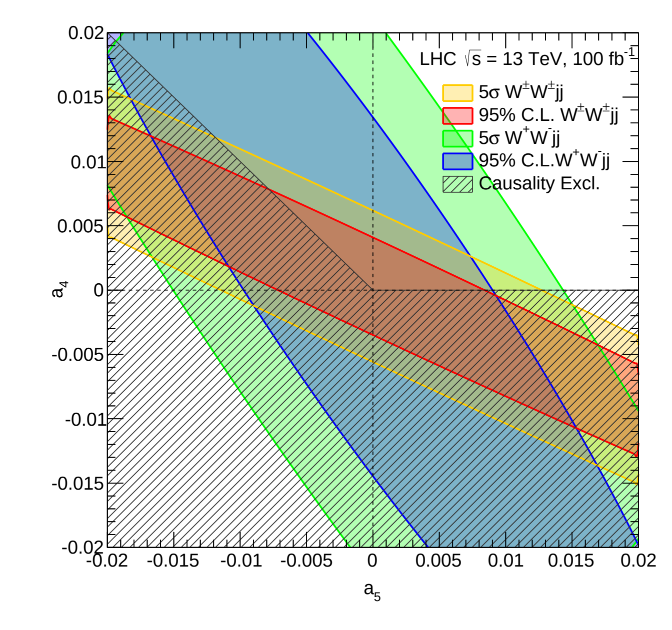
- $pp \to W^{\pm}W^{\pm}jj$ SS channel

	CL 95%	CL 99%	3σ	5σ
a_5	$-0.007 \div 0.008$	$-0.009 \div 0.010$	$-0.008 \div 0.010$	$-0.011 \div 0.013$
a_4	$-0.004 \div 0.004$	$-0.005 \div 0.005$	$-0.004 \div 0.005$	$-0.006 \div 0.006$
a_3	$-0.07 \div 0.10$	$-0.10 \div 0.12$	$-0.09 \div 0.10$	$-0.12 \div 0.14$
a_2	$-1.2 \div 1.6$	$-1.6 \div 2.0$	$-1.4 \div 1.8$	$-2.0 \div 1.5$
a	$0.2 \div 1.5$	$-0.4 \div 1.6$	$-0.1 \div 1.6$	$-1.6 \div 1.7$

- $pp \to W^{\pm}W^{\mp}jj$ OS channel

	CL 95%	CL 99%	3σ	5σ
a_5	$-0.010 \div 0.009$	$-0.012 \div 0.011$	$-0.011 \div 0.011$	$-0.015 \div 0.014$
a_4	$-0.014 \div 0.014$	$-0.018 \div 0.018$	$-0.016 \div 0.017$	$-0.022 \div 0.022$
a_3	$-0.15 \div 0.20$	$-0.20 \div 0.25$	$-0.18 \div 0.22$	$-0.25 \div 0.30$
a_2	$-1.1 \div 1.2$	$-1.4 \div 1.5$	$-1.3 \div 1.4$	$-1.7 \div 1.8$
a	$-0.4 \div 1.8$	$-0.7 \div 2.1$	$-0.6 \div 2.0$	$-0.9 \div 2.4$

2D limits



LHC √s = 13 TeV, 100 fb-1
5σ W±W±jj
95% C.L. W±W±jj
5σ W+W-jj
95% C.L.W+W-jj
Causality Excl.
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
a4
-0.02
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02
a5

$\sqrt{s} = 13$ **TeV** **L=300 fb^{-1}**

1D limits and significance

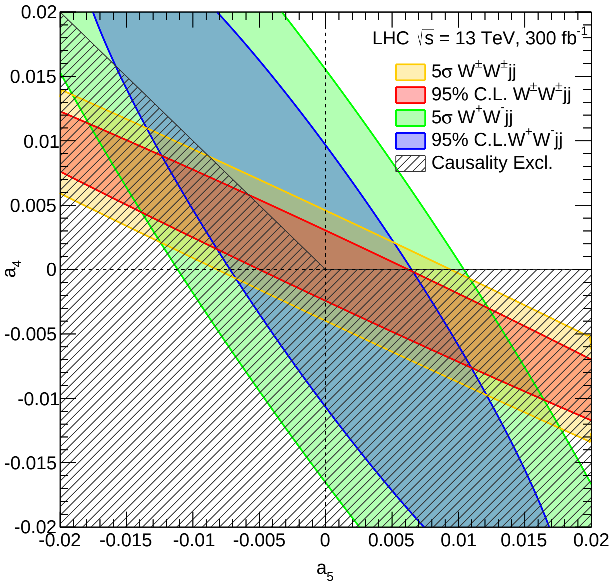
- $pp \to W^{\pm}W^{\pm}jj$ SS channel

	CL 95%	CL 99%	3σ	5σ
a_5	$-0.005 \div 0.006$	$-0.006 \div 0.008$	$-0.006 \div 0.007$	$-0.008 \div 0.009$
a_4	$-0.002 \div 0.003$	$-0.003 \div 0.004$	$-0.003 \div 0.004$	$-0.004 \div 0.005$
a_3	$-0.05 \div 0.07$	$-0.07 \div 0.09$	$-0.06 \div 0.09$	$-0.08 \div 0.11$
a_2	$-0.8 \div 1.2$	$-1.1 \div 1.5$	$-1.0 \div 1.4$	$-1.4 \div 1.8$
a	$0.5 \div 1.4$	$0.3 \div 1.5$	$0.4 \div 1.5$	$-0.1 \div 1.6$

- $pp \to W^{\pm}W^{\mp}jj$ OS channel

	CL 95%	CL 99%	3σ	5σ
a_5	$-0.007 \div 0.006$	$-0.009 \div 0.008$	$-0.008 \div 0.008$	$-0.011 \div 0.010$
a_4	$-0.010 \div 0.010$	$-0.013 \div 0.013$	$-0.012 \div 0.012$	$-0.016 \div 0.016$
a_3	$-0.10 \div 0.15$	$-0.13 \div 0.18$	$-0.13 \div 0.18$	$-0.17 \div 0.22$
a_2	$-0.8 \div 0.9$	$-1.0 \div 1.1$	$-0.9 \div 1.0$	$-1.2 \div 1.3$
a	$-0.2 \div 1.6$	$-0.3 \div 1.8$	$-0.3 \div 1.7$	$-0.5 \div 2.0$

2D limits



LHC √s = 13 TeV, 300 fb-1
5σ W±W±jj
95% C.L. W±W±jj
5σ W+W-jj
95% C.L.W+W-jj
Causality Excl.
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.02
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02
a4
a5

$\sqrt{s} = 14$ **TeV** **L=3000 fb^{-1}**

1D limits and significance

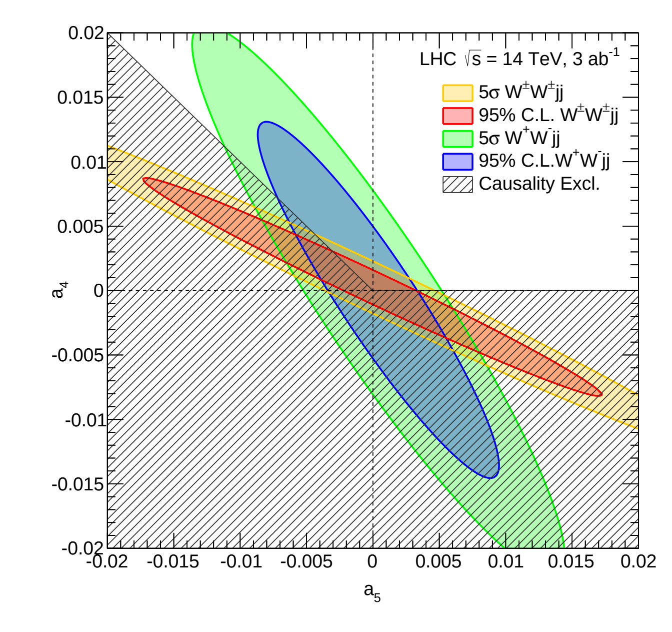
- $pp \to W^{\pm}W^{\pm}jj$ SS channel

	CL 95%	CL 99%	3σ	5σ
a_5	$-0.002 \div 0.003$	$-0.003 \div 0.004$	$-0.003 \div 0.004$	$-0.004 \div 0.005$
a_4	$-0.001 \div 0.002$	$-0.001 \div 0.002$	$-0.001 \div 0.002$	$-0.002 \div 0.002$
a_3	$-0.02 \div 0.05$	$-0.03 \div 0.05$	$-0.03 \div 0.05$	$-0.04 \div 0.06$
a_2	$-0.3 \div 0.8$	$-0.4 \div 0.9$	$-0.4 \div 0.8$	$-0.6 \div 1.0$
a	$0.9 \div 1.3$	$0.8 \div 1.3$	$0.8 \div 1.3$	$0.7 \div 1.3$

- $pp \to W^{\pm}W^{\mp}jj$ OS channel

	CL 95%	CL 99%	3σ	5σ
a_5	$-0.003 \div 0.003$	$-0.004 \div 0.004$	$-0.004 \div 0.004$	$-0.005 \div 0.005$
a_4	$-0.006 \div 0.004$	$-0.007 \div 0.006$	$-0.007 \div 0.005$	$-0.008 \div 0.007$
a_3	$-0.06 \div 0.08$	$-0.08 \div 0.09$	$-0.07 \div 0.09$	$-0.10 \div 0.11$
a_2	$-0.4 \div 0.4$	$-0.5 \div 0.5$	$-0.5 \div 0.5$	$-0.6 \div 0.6$
a	$0.5 \div 1.4$	$0.3 \div 1.4$	$0.4 \div 1.4$	$-0.1 \div 1.5$

2D limits


LHC $\sqrt{s}$ = 14 TeV, 3 ab^{-1}
5σ $W^{\pm}W^{\pm}jj$
95% C.L. $W^{\pm}W^{\pm}jj$
5σ $W^{+}W^{-}jj$
95% C.L.$W^{+}W^{-}jj$
Causality Excl.
a_4
a_5
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.02
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02

Summary and conclusions

- WW scattering is the best laboratory to study EW symmetry breaking
- R_{p_T} variable turned out to be very effective for the SS channel $pp \to W^{\pm}W^{\pm}jj$
- best expected exclusion limits for a_4 and a_5 at LHC13 with 100 fb^{-1}
- for a_3, competitive with today's limits only at LHC Run 3
- for a_2, competitive with today's limits only at HL-LHC

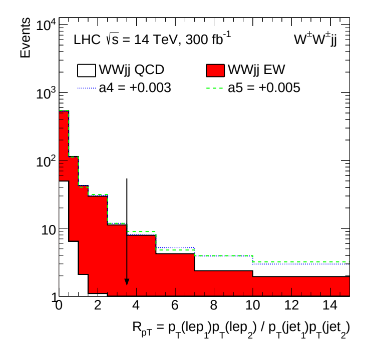
What is missing...

- improve selection cuts for OS channel $pp \to W^{\pm}W^{\mp}jj$
- evaluate the impact of missing backgrounds
- include properly systematic uncertainties
- NLO corrections (?)

Thank you!

BACKUP

R_{p_T} vs. $p_T(lep)$



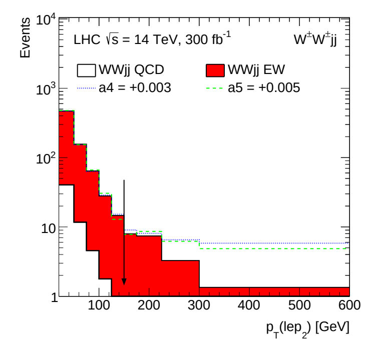


Figure: *Comparison of selection cuts:* $R_{p_T} > 3.5$ *vs.* $p_T^{lep} > 150\ GeV$. *In red (white) the EW (QCD) contribution. The dashed lines mark the number of events in the presence of non-vanishing coefficients of the effective lagrangian* ($a_4 = 0.003$ *and* $a_5 = 0.005$)

OS cuts

- two OS leptons with $p_T^{l\pm} > 20$ GeV and $|\eta_{l\pm}| < 2.5$;
- missing transverse energy $E_T^{miss} > 25$ GeV
- two hardest jets with an invariant mass $m_{jj} > 500$ GeV;
- two and only two jets ($p_T^j > 25$ GeV and $|\eta_j| < 4.5$) with relative rapidity $|\Delta y_{jj}| > 2.4$;
- $R_{p_T} > 3.5$;
- invariant transverse mass $m_T^{WW} > 800$ GeV;
- lepton angular separation in the transverse plane $|\Delta\Phi_{ll}| > 2.25$;
- b-quark veto (*i.e.* no jets tagged by the b-tagging algorithm implemented in `Delphes`).

Invariant tranverse mass

$$m_T^{WW} = \sqrt{\left(\sqrt{(p_T^{ll})^2 + m_{ll}^2} + \sqrt{(E_T^{miss})^2 + m_{ll}^2}\right)^2 - (\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss})^2}$$

OS cut flow

$\sqrt{s} = 14$ TeV, 300 fb^{-1}				
cut	$t\bar{t}$	$WWjj$ QCD	$WWjj$ EW	S ($a_5 = 0.02$)
2 OS leptons	1975270	68884	3221	498
$E_T^{miss} > 25$ GeV	1791100	61494	2927	488
$m_{jj} > 500$ GeV	109885	6761	1569	380
$\Delta y_{jj} > 2.4$	78144	4543	1369	394
$R_{p_T} > 3.5$	1461	114	44	287
$m_T^{WW} > 800$ GeV	504	40	19	231
$\Delta\Phi_{\ell\ell} > 2.25$	453	34	19	231
b-tag veto	353	34	19	227
N jets < 3	21	14	11	148

K-matrix vs. sharp cut-off

Values obtained by using the SS WW channel

	$\sqrt{s} = 14$ TeV, 300 fb^{-1}			
	K-matrix		sharp cut off ($E_{WW} < 1.25$ TeV)	
	95% (99%)	3σ (5σ)	95% (99%)	3σ (5σ)
a_4	0.0028 (0.0038)	0.0035 (0.0053)	0.0027 (0.0034)	0.0032 (0.0041)
a_5	0.0053 (0.0072)	0.0066 (0.0107)	0.0055 (0.0068)	0.0064 (0.0084)